Last results on ϵ'/ϵ from NA48

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1) What is ϵ'/ϵ ?
2) NA48 Method and Detector
3) 98 Data Analysis and Result
4) Prospects and Conclusions

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on behalf of NA48 COLLABORATION

Cagliari, Cambridge, CERN, Dubna, Edinburgh,
Ferrara, Firenze, Mainz, Orsay, Perugia, Pisa,
Saclay, Siegen, Torino, Warsaw, Wien

I. What is ϵ'/ϵ ?

In the neutral kaon system :

- $K^0(\bar{s}d)$ and $\overline{K^0}(s\bar{d})$ are eigenstates of strong interaction.
- K_1 and K_2 are CP eigenstates

$$K_1 = (K^0 + \overline{K^0})/\sqrt{2}(CP = +1)$$
$$K_2 = (K^0 - \overline{K^0})/\sqrt{2}(CP = -1)$$

Weak interactions allow $\Delta S = 1$ or 2 transitions.
If CP is a good symmetry, the physical states would be K_1 and K_2
K_1 can decay to two pions (CP=+1)
K_2 cannot decay to two pions

- 1964 : CP violation discovery

$\Rightarrow$ Mass eigenstates are not pure CP eigenstates :

$K_S \simeq$	$K_1 +$	$\varepsilon.K_2$	$K_L \simeq$	$K_2 +$	$\varepsilon.K_1$
69 %	$\pi^+\pi^-$		21 %	$3\pi^0$	
31 %	$\pi^0\pi^0$		13 %	$\pi^+\pi^-\pi^0$	
			27 %	$\pi\mu\nu$	
			39 %	$\pi e\nu$	
			0.2 %		$\pi^+\pi^-$
			0.1 %		$\pi^0\pi^0$

$c\tau_S = 2.67\ cm$ $\qquad$ $c\tau_L = 15.5\ m$

$$\boxed{|\varepsilon| = (2.28 \pm 0.02)\ 10^{-3}}$$

indirect CP violation

Direct CP Violation :

$$|A(K^0 \to f\bar{f})| \neq |A(\overline{K^0} \to f\bar{f})|$$

Need interference of two decay amplitudes

Two pion state from K^0 can have I=0 or 2 $\Rightarrow$ 2 amplitudes A_0 and A_2

$$\begin{array}{ccccc} \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} & \equiv & \eta^{+-} & = & \epsilon + \epsilon' \\ \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} & \equiv & \eta^{00} & = & \epsilon - 2\epsilon' \end{array}$$

$$\epsilon' = \frac{i}{\sqrt{2}} Im\left(\frac{\mathcal{A}_2}{\mathcal{A}_0}\right) e^{i(\delta_2 - \delta_0)}$$

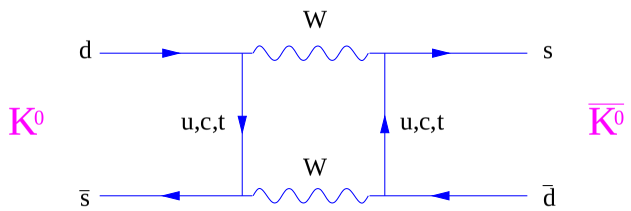
Experimental observable :

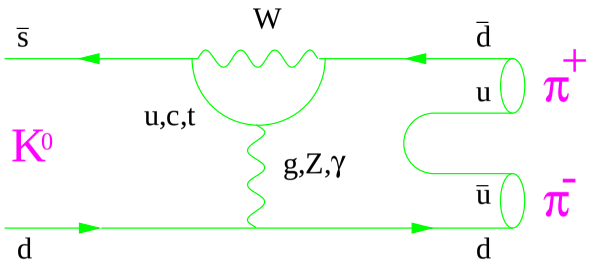
$$\begin{array}{ccc} \mathrm{R} & \equiv & \frac{\Gamma(K_L \to \pi^0\pi^0)\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^0\pi^0)\Gamma(K_L \to \pi^+\pi^-)} \\ & = & 1 - 6\ \mathrm{Re}(\epsilon'/\epsilon) \end{array}$$

Direct CP Violation $\Leftrightarrow$ R $\neq$ 1

Standard Model predictions

Indirect violation
through mixing
$K^0/\overline{K^0}$ oscillations
$\Rightarrow \varepsilon$ parameter





Direct violation
through decay
penguin diagrams
$\Rightarrow \varepsilon'$ parameter

Typical theoretical predictions :
ϵ'/ϵ between $\approx$ fews 10^{-4} and $\approx 2.10^{-3}$.

Previous Measurements of Re(ε'/ε)	NA31	$(23.0 \pm 6.5) \times 10^{-4}$	$(3.5\ \sigma)$
	E731	$(7.4 \pm 5.9) \times 10^{-4}$	$(1.2\ \sigma)$
	KTEV	$(28.0 \pm 4.1) \times 10^{-4}$	$(6.8\ \sigma)$
	NA48	$(18.5 \pm 7.3) \times 10^{-4}$	$(2.5\ \sigma)$

II. NA48 method and detector

- Goal : measure $\mathrm{Re}(\varepsilon'/\varepsilon)$ (final precision $\approx 2 \times 10^{-4}$)

- Mean : measure the double ratio of the four modes

$$R = \frac{N(\mathrm{K_L} \to \pi^0\pi^0)N(\mathrm{K_S} \to \pi^+\pi^-)}{N(\mathrm{K_S} \to \pi^0\pi^0)N(\mathrm{K_L} \to \pi^+\pi^-)} \simeq 1 - 6\mathrm{Re}(\varepsilon'/\varepsilon)$$

$\Leftrightarrow$ Count number of events

Principles to keep systematic effects at low level :

- The 4 modes are taken simultaneously
- From the same fiducial volume (life time $< 3.5 \times \tau_S$)

$\Rightarrow$ Cancellation of flux, dead times, inefficiencies, accidental losses...

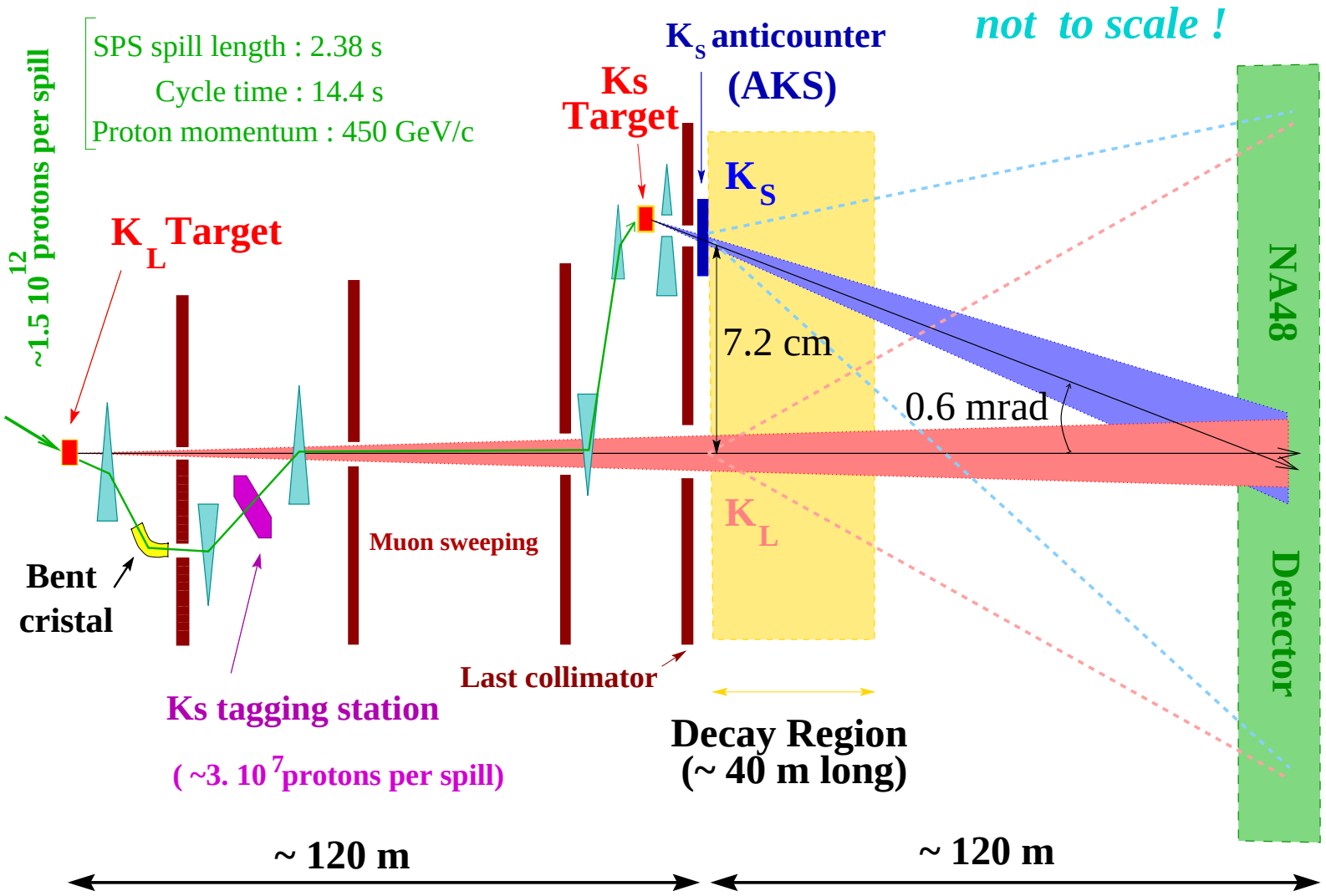
- Apply lifetime weighting to equalize distribution of $\mathrm{K_S}$ and $\mathrm{K_L}$ decay positions

$\Rightarrow$ Cancellation of detector acceptance effects

- Analysis in bins of energy to get rid of slight differences of $\mathrm{K_S}$ and $\mathrm{K_L}$ energy spectra (20 bins 70–170 GeV)
- Use quasihomogoneous Liquid Krypton calorimeter to detect $\pi^0\pi^0$ and magnetic spectrometer for $\pi^+\pi^-$

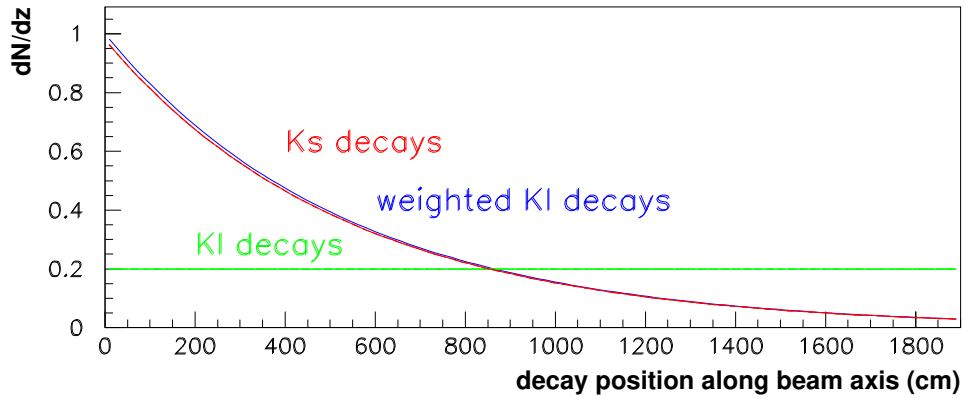
$\Rightarrow$ Minimize backgrounds

NA48 simultaneous and collinear K_S and K_L beams



K_S and K_L beams are distinguished by proton tagging upstream of the K_S target.

Weighting principle :



- At E(K) $\approx$ 100 GeV, $\beta\gamma c\tau_{KS} \approx 540$ cm
- Weight K_L events with W $= e^{-z/(\beta\gamma c)(1/\tau_{KS}-1/\tau_{KL})}$

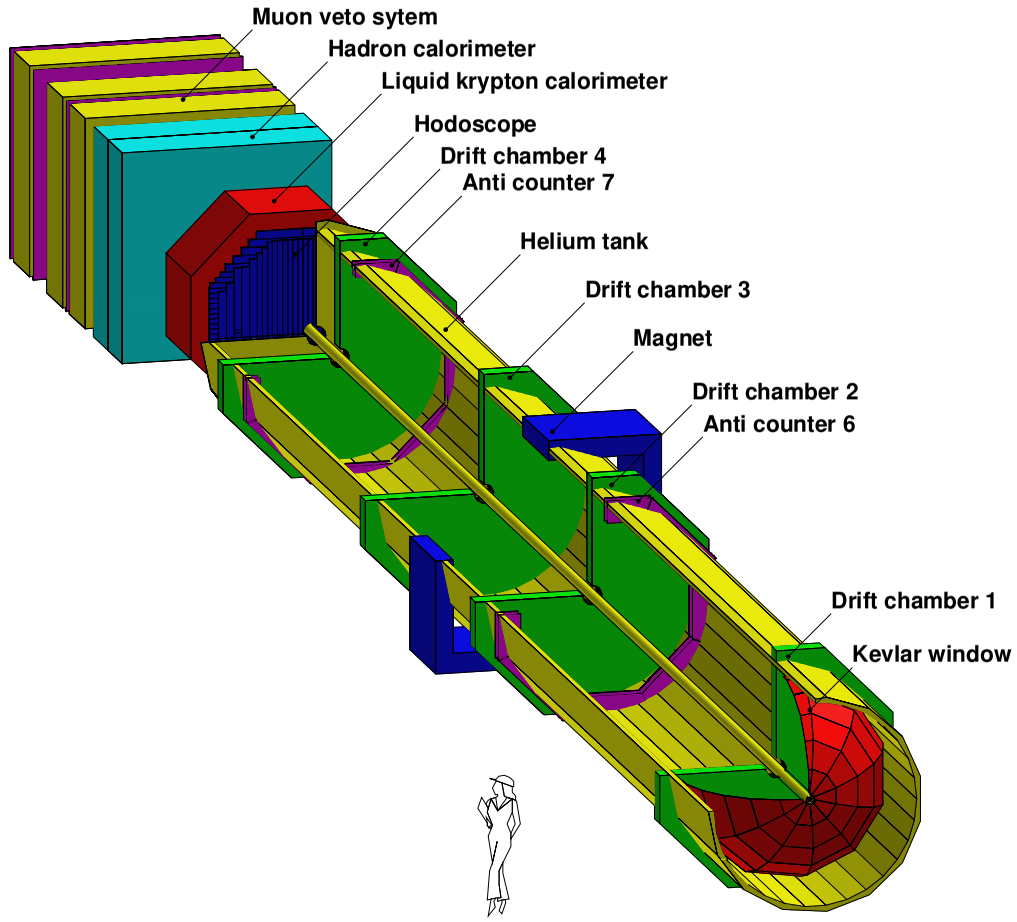
$\Rightarrow$ Weigthed $K_L = K_S$ for the detector

$\Rightarrow$ Same geometrical acceptance, no effect from detector inefficient regions

$\Rightarrow$ Reduce systematic effects

- Price : Increase of the statistical error

NA48 detector

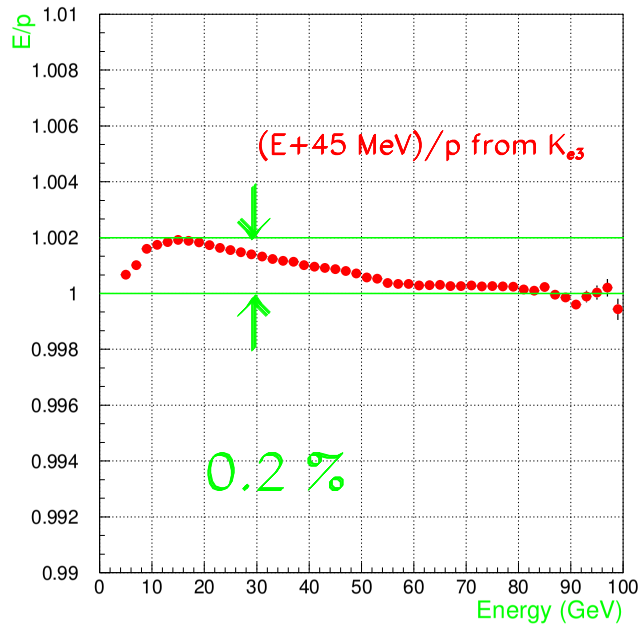


- $K_{\mathrm{L,S}} \to \pi^+\pi^-$
  - Magnetic spectrometer ($\sigma_{X,Y} \sim 90\ \mu\mathrm{m}$)
  - $\sigma(P)/P \simeq 0.5\,\% \oplus 0.009\ P[\mathrm{GeV}/c]\,\%$ (~ 1 % for 100 GeV/c track momentum)
  - Hodoscope for timing measurements ($\sigma_t \sim 200\ ps$)
  - Muon veto to reject $\pi\mu\nu$ background.

- $K_{\mathrm{L,S}} \to \pi^0\pi^0$
  - Liquid Krypton electromagnetic calorimeter ($\sigma_t \sim 250\ ps$)

Calorimeter performances

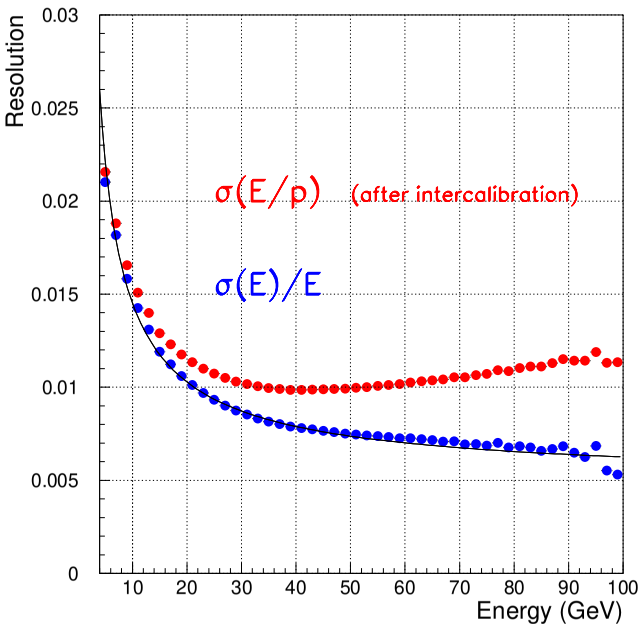
Using electrons from $\pi e \nu$ decay as a probe



- Linearity

$$\frac{Energy(LKR)}{Momentum(DCH)}$$

$\Rightarrow$ Non-Linearity $< 0.2\%$ (from 5 to 100 GeV)



- Resolutions

E/P resolution

drift chamber deconvoluted

$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{100\ MeV}{E} \oplus 0.5\%$$

III. 98 Data analysis and Result

Data samples :

- 1997 run : 42 days at 1×10^{12} ppp on K_L target

  $\Rightarrow$ 0.49 million of $K_L \to \pi^0\pi^0$

  PUBLISHED Phys. Lett. B 465 (1999) 335-348

  $$\mathrm{Re}(\varepsilon'/\varepsilon) = (18.5 \pm 4.5 \pm 5.8) \times 10^{-4}$$

- 1998 run : 105 days $\sim 1.4 \times 10^{12}$ ppp on K_L target

  Main improvements :
  - LKr High Voltage 1500 $\to$ 3000 V
  - Charged trigger efficiency 91.3 $\to$ 97.7 %
  - Downscaling factor of 2 removed in charged trigger
  - Lighter beam pipe $\to$ less activity
  - New data acquisition system (PC farm) + 30 % rate

  $\Rightarrow$ 1.14 million of $K_L \to \pi^0\pi^0$

  PRELIMINARY RESULT in this presentation

- 1999 run : 124 days $\sim 1.4 \times 10^{12}$ ppp on K_L target

  $\Rightarrow$ Around 2 millions of $K_L \to \pi^0\pi^0$

  Analysis in progress...

Analysis path :

$$R = \frac{N(\mathrm{K_L} \to \pi^0\pi^0)N(\mathrm{K_S} \to \pi^+\pi^-)}{N(\mathrm{K_S} \to \pi^0\pi^0)N(\mathrm{K_L} \to \pi^+\pi^-)}$$

- Identify $\pi^+\pi^-$ and $\pi^0\pi^0$ events
  and subtract small residual backgrounds
- Identify $\mathrm{K_L}$ and $\mathrm{K_S}$ events with the tagger
  check misidentification probabilities
- Define same fiducial region to count $\pi^+\pi^-$ and $\pi^0\pi^0$
  (energy scale definition and non linearities)
- Weight $\mathrm{K_L}$ events and correct for small residual
  acceptance difference
- Check other systematic effets : trigger efficiencies,
  events loss related to beam intensity, ...

$\pi^+\pi^-$ Selection

K_S : No background
K_L : Background from CP conserving $\pi\mu\nu$ and $\pi e\nu$ decays

Background rejection

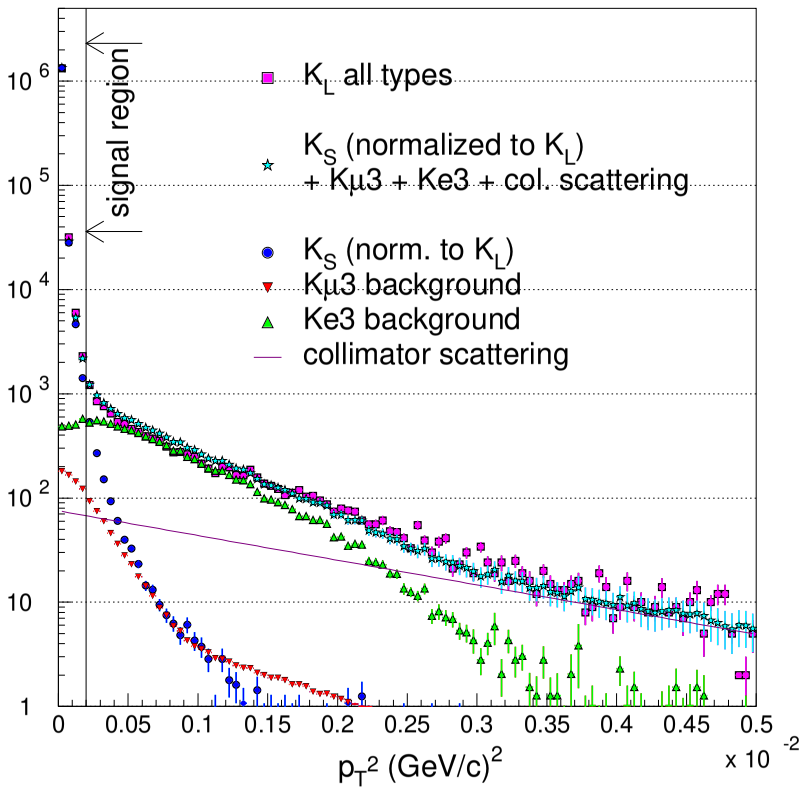
$\pi\mu\nu$: no hit in μ veto
$\pi e\nu$: $\frac{E_{LKr}}{P_{DCh}} < 0.8$

$\pi\pi$ mass within 3σ
($\sigma \approx 2.5$ MeV/c^2)

$p_t^2 < 200\ (MeV/c)^2$

Background subtraction

Fit K_L distribution as
$\pi^+\pi^- + \pi\mu\nu + \pi e\nu$
(in a wide $m_{\pi\pi} \times p_t$ control region)



Overall background = $(19 \pm 3) \times 10^{-4}$

$\pi^0\pi^0$ Selection

K_S: No background

K_L: Background from CP conserving $\pi^0\pi^0\pi^0$ decays

- Measure (E,x,y) of 4 γ in calorimeter
- Reconstruct decay vertex position assuming Kaon mass for 4 γ:

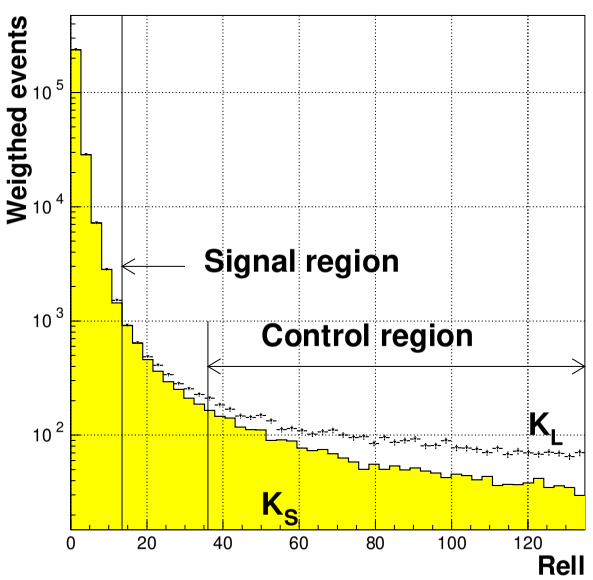
$$D = \sqrt{\Sigma E_i E_j d_{ij}^2}/M_K$$

- Photon pairing to get best π^0 masses :

$$m_{ij} = \sqrt{E_i E_j} d_{ij}/D \ (\sigma \approx 1 \text{ MeV/c}^2)$$

- Define pseudo χ^2 to separate signal and background :

$$R_{ell} \equiv \left\{ \left(\frac{\frac{m_1+m_2}{2} - m_{\pi^0}}{\sigma_+} \right)^2 + \left(\frac{\frac{m_1-m_2}{2}}{\sigma_-} \right)^2 \right\}$$



Background subtraction

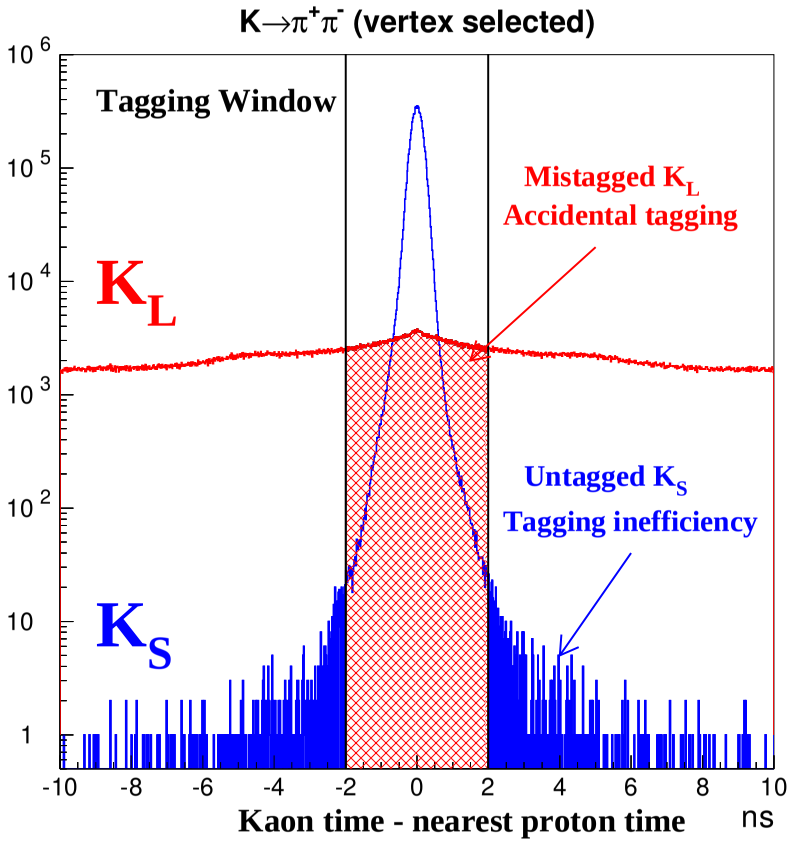
Signal region :
$R_{ell} < 13.5$

$K_L - K_S$ in control region
$\rightarrow$ background

$= \boxed{(6.6 \pm 2.0).10^{-4}}$

Tagging : K_L / K_S identification

Plot : event time – nearest proton time



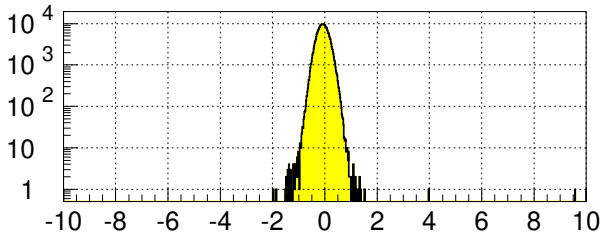
In the charged modes only, identification can also be done by vertex reconstruction.

- Tagging inefficiency: K_S taken as K_L
$$\alpha_{SL}^{+-} = (1.97 \pm 0.05) \times 10^{-4}$$
- Accidental tagging: K_L taken as K_S
$$\alpha_{LS}^{+-} = (11.05 \pm 0.01)\%$$

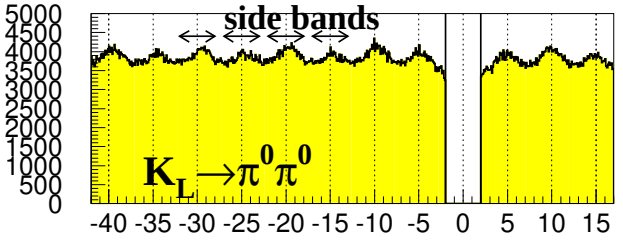
Effect on R if difference between neutral and charged modes

- $\Delta R \approx 6\ \Delta\alpha_{SL}$
- $\Delta R \approx 2\ \Delta\alpha_{LS}$

Tagging : Neutral vs Charged



Neutral - Charged time in conversion (ns)



Time of protons - event time in K_L events (ns)

$\Delta\alpha_{SL}$:

Use conversions to compare neutral and charged times

$\Rightarrow \Delta\alpha_{SL} < 0.5 \times 10^{-4}$

$\Rightarrow \Delta R < 3 \times 10^{-4}$

$\Delta\alpha_{LS}$:

Use side-bands to compare proton rates in K_L to $\pi^+\pi^-$ and $\pi^0\pi^0$

$\rightarrow \Delta\beta = (5.3 \pm 1.6) \times 10^{-4}$

Extrapolate to event time with K_L to $\pi^+\pi^-$ and $\pi^0\pi^0\pi^0$

$\rightarrow \Delta W = (-5.0 \pm 3.9) \times 10^{-4}$

$\Rightarrow \Delta\alpha_{LS} = (0.3 \pm 4.2) \times 10^{-4}$

$\Rightarrow \Delta R = (0.6 \pm 8.4) \times 10^{-4}$

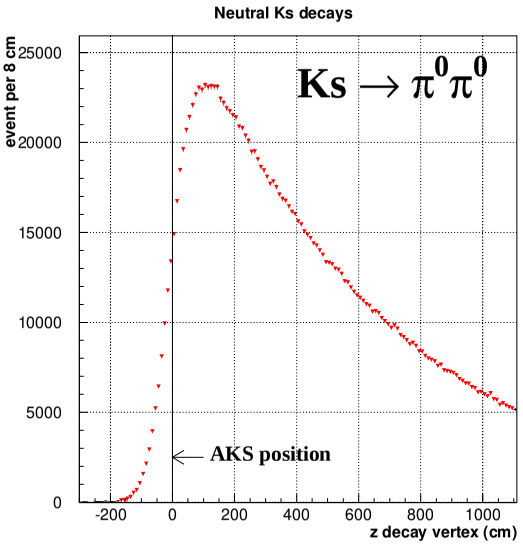
Calorimeter energy scale

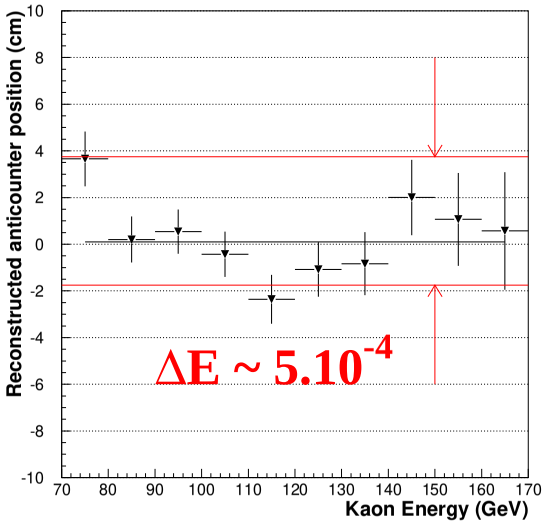
Energy scale

In the neutral mode : $D = \sqrt{\sum E_i E_j \times (r_{ij})^2}\ /M_K$

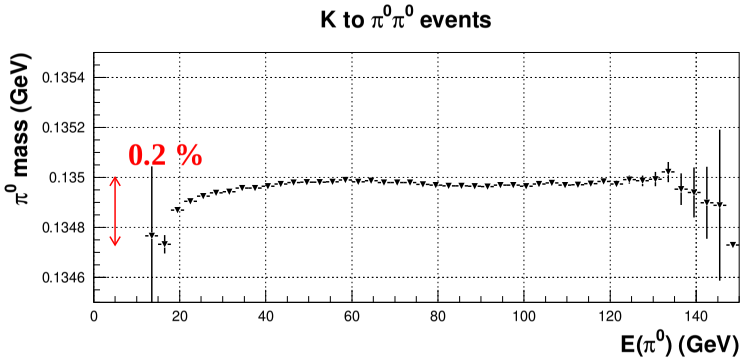
$\Rightarrow$ Need good knowledge of Energy scale to define fiducial region

Known anti-K_S counter position $\rightarrow$ adjust Energy scale (1 factor)





Non Linearity ($\Leftrightarrow$ energy dependence of the scale)

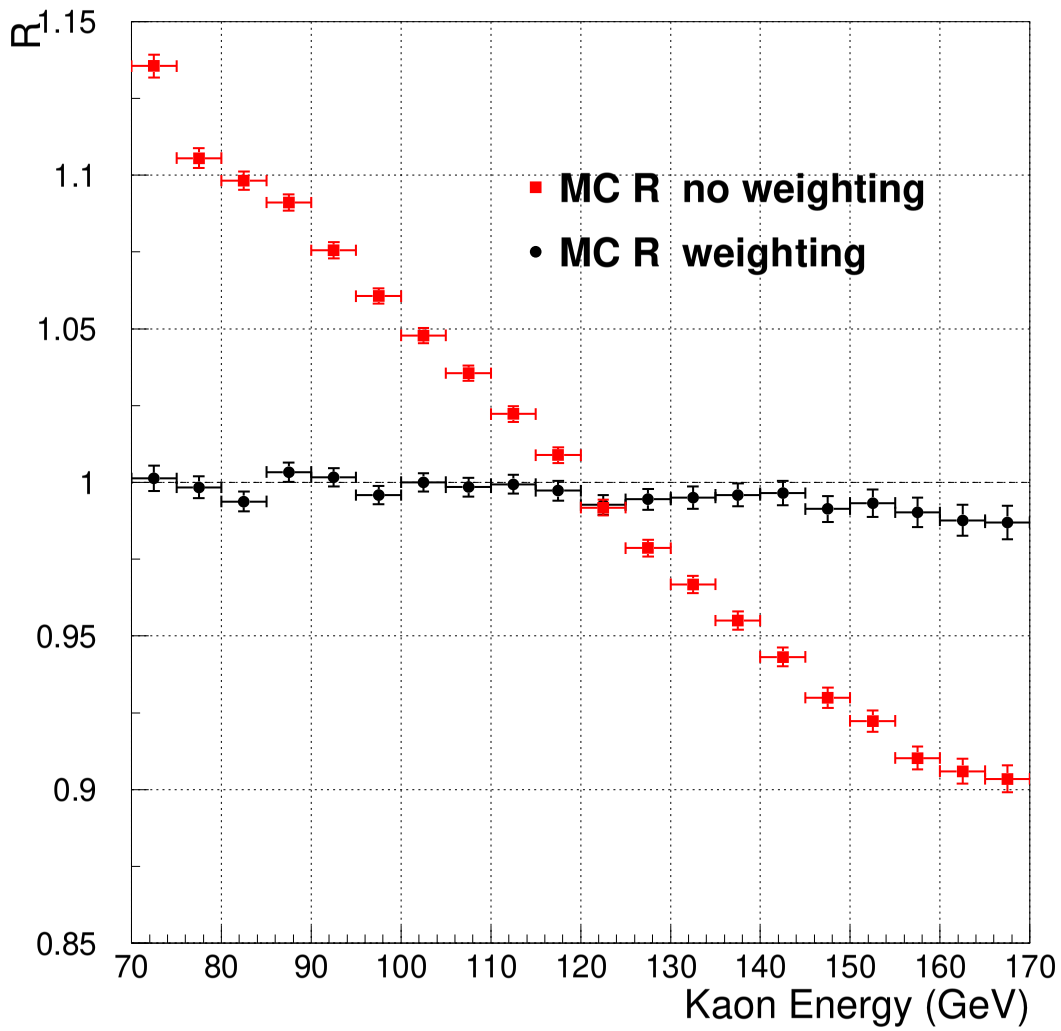


Non-linearity (5.10^{-4}) $\oplus$ energy scale (3.10^{-4}) $\oplus$ transverse scale (3.10^{-4}) $\oplus$ non-gaussian tails (5.10^{-4}) $\oplus$...

$\Rightarrow$ Uncertainty on R : $10. \times 10^{-4}$

Acceptance Correction

Weighting Kl events minimizes the acceptance correction
A Monte-Carlo is used to evaluate the small residual effects



$Delta R = 30.3 \pm 7.4$ (MC stat.) ± 6.0 (syst.) $\times 10^{-4}$

Event counts in 98 data

Mode	Statistics (millions)
$K_S \to \pi^+\pi^-$	7.46
$K_L \to \pi^+\pi^-$	4.87
$K_S \to \pi^0\pi^0$	1.80
$K_L \to \pi^0\pi^0$	1.14

(after correcting for accidental tagging)

Statistical uncertainty on R :

(taking weighting into account)

$$17.3 \times 10^{-4}$$

Correction and systematic uncertainties

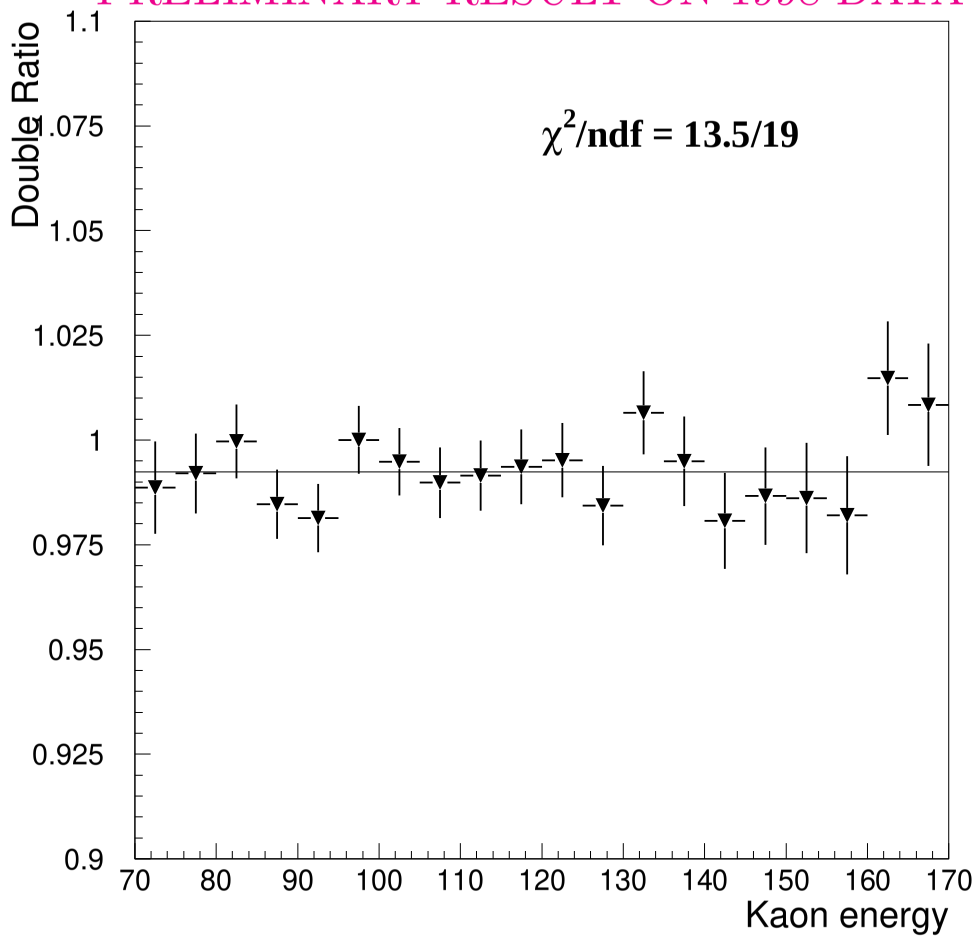
Corrections and uncertainties on R (Unit = 10^{-4})		
Source	1998 sample	
Charged trigger	–1.4	11.5
Accidental tagging	+0.6	8.5
Tagging efficiency	–	3.0
Neutral E-scale	–	10.2
Charged vertex	+2.0	2.0
Acceptance	+31.1	8.7
Neutral BG	–6.6	2.0
Charged BG	+19.0	3.0
Beam scattering	–9.9	3.0
Accid. activity	+2.0	12.2
Total	+36.8	23.8

$$\mathrm{Re}(\varepsilon'/\varepsilon) = \frac{1}{6} \times (1 - R)$$

Errors in green = limited by data statistic
Errors in blue = work in progress to improve for final result

ϵ'/ϵ result

PRELIMINARY RESULT ON 1998 DATA



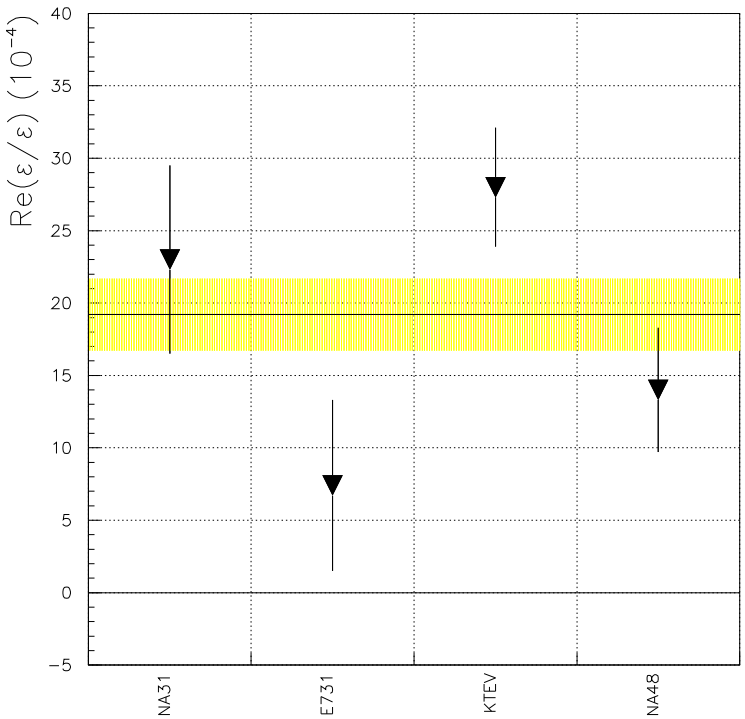
$$\Rightarrow \mathrm{Re}(\varepsilon'/\varepsilon) = (12.2 \pm 2.9(\mathrm{stat.}) \pm 4.0(\mathrm{syst.})) \times 10^{-4}$$

Combining with published 97 result,

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (14.0 \pm 4.3) \times 10^{-4}}$$

IV) Prospects and Conclusions

Experimental situation



World Average value

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (19.2 \pm 2.5) \times 10^{-4}$$

but $\chi^2/\mathrm{dof} = 10.4/3$!

$\Rightarrow$

$\epsilon'/\epsilon \neq 0$ well established
but exact value debatable

Prospects

NA48 :

- Finalize systematic errors for 98 and analyze 99 data
  ($\approx 2\times10^6$ K_L to $\pi^0\pi^0$, twice as much as 98 data)
  Expected accuracy $\approx$ 2.5 to 3 $\times$ 10^{-4} on ϵ'/ϵ
- End of 99, implosion of beam tube $\rightarrow$ drift chambers damaged
  In 2000, perform systematic checks with neutral events
  Drift chambers repair underway $\rightarrow$ run in 2001 for ϵ'/ϵ

- KTeV : new result on full 97 sample expected soon
  (99 sample similar size as 97 sample)

- KLOE : very different method

Conclusions

- New NA48 preliminary result :

  $Re(\epsilon'/\epsilon) = (14.0 \pm 4.3) \times 10^{-4}$

- CP asymetry in a decay process :

  $\frac{\Gamma(K_0 \to \pi^+\pi^-) - \Gamma(\overline{K_0} \to \pi^+\pi^-)}{\Gamma(K_0 \to \pi^+\pi^-) + \Gamma(\overline{K_0} \to \pi^+\pi^-)} = (4.5 \pm 1.4) \times 10^{-6}$

- Current world average is :

  $Re(\epsilon'/\epsilon) = (19.2 \pm 2.5) \times 10^{-4}$
  but with a poor χ^2

- $Re(\epsilon'/\epsilon) \neq 0$ established

- More results to come and hopefully to clarify experimental situation